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A Control Topology to Enhance Performance of Weak Grid under Different Power Levels

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Abstract: ***The main objective of this paper is to provide a new control topology for improving the performance of weak grid by damping power and frequency oscillations. To attenuate power and frequency oscillations, a linear controller is used based on droop characteristics. The controller has cascaded angle, frequency and power loops for frequency and angle regulation. The controller provides new control technique for VSC to damp power and frequency oscillations by automatically synchronizing the VSC to grid. The linear controller can also be suitable for both islanded and grid connected operation without reconfiguration. The controller offers stable and smooth operation. Also analysis of system performance at low and high-power references, transition to islanding, self-synchronization were carried out.***

Keywords: Distributed generation, Linear control, Power damping, Voltage source converter (VSC) control, Weak grid

List of Nomenclature

E	VSC voltage amplitude
E_0	Rated line voltage
E_F	Filter voltage
$E_{F\text{-}ref}$	Filter voltage command.
K_d	Power-angle characteristics slope.
K_f	Power-frequency characteristics slope.
Kp	Power loop integrator gain
K_v	Proportional gain of the voltage controller
K_{vi}	Integrator gain of the voltage controller
K_q	Proportional gain of the reactive power controller
K_{qi}	Integrator gain of the reactive controller
P	VSC output real power
P_{damp}	Damping power
P_{set}	Reference Real power of VSC
P_{synch}	Synchronization power
Q	VSC output reactive power.
R	Total connecting resistance
R_F	Filter resistance
V_L	Local load bus voltage amplitude
X	Total connecting reactance
X_F	Filter reactance
Z	Total impedance
δ	VSC voltage angle
ω	VSC frequency.
ω_0	Rated frequency
ω_{set}	Set Frequency
ω_v	Cut-off frequency of the voltage loop low-pass filter

1. Introduction

Distributed generation (DG) units can be empowered by clean or renewable resources, such as fuel cells, photovoltaic (PV), micro-turbines and wind turbines. Due to fast development of power electronic devices, the majority of DG units are interfaced to the grid through power converters. The High Voltage Direct Current Transmission (HVDC) and FACTS systems are important technologies, supporting in their own way the modern power systems. In many cases, they are fully or partially deregulated in several countries. Both HVDC and FACTS systems were initially based on thyristor technology, but nowadays, they are fully controlled on semiconductors and voltage source converter topologies.

Especially, the Voltage Source Converter topology is becoming a standard, modular, solution for many applications due to its capacity for reversible power flow, for DC voltage control and for the implementation of high performance control systems and also it is preferable for its advantages such as black starting capability, reactive power support to the ac system, lower cable cost and possibility to connect to very weak ac systems. When compared to thyristor based system, high frequency PWM waveforms are generated by voltage source converter.

In weak grid, the voltage levels are not constant as that of a stiff grid and it is necessary to take the voltage level, fluctuations into account, particularly in case of load and production where the value may exceeds the standard requirements. It is generally accepted that weak ac grids cause stability and power quality issues, historically this phenomenon has been challenging to further study. When DG is integrated with weak grids (high impedance grids), there arises the challenging issues. This objective gains its importance due to high and fast penetration level of off-shore wind turbines and remote PV generation units. In fact, the grid stiffness is a measure of the connecting line capacity to transfer power to a grid. In other words, weak ac grids encounter more difficulty in power flow transfer, thus the maximum amount of available power that can be injected to the grid is more limited.

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There are many ways of control methods, which can be implemented for the grid-connected VSC. But the most preferably implemented methods are such as power-angle control and vector-current control. In the power angle control, by changing the voltage magnitude of VSC, the reactive power can be controlled and the phase angle shift between the ac system and voltage source converter the active power can be controlled. Though the power angle control is been implemented in the application of wind turbine, STATCOM and HVDC, It has two most important demerits with it. Firstly, it has the poor performance in limiting the current flow on the converter. In order to protect the converter from tripping, the valve current has to be limited particularly in high power application. Second, the vector current control by the name itself, it is clear that it has basic nature of limitation in current flow of a converter. Since the vector current control has inner current control loop, it can easily control both active and reactive power. The vector current control method is the most effective one in grid-connected VSCs, but this cannot accept when VSC is connected to a weak ac system. A major drawback of vector control is its limited capability to transfer the rated power in weak grids.

To overcome the above difficulties, a synchronization control concept is implemented. The power-synchronization control has shown to be particularly suitable for controlling a VSC which is connected to weak ac systems. In some sense, power synchronization control might be viewed upon as a combination of vector current control and power angle control. The power synchronization is an alternative to a normal Phase Lock Loop(PLL). The power synchronization control can directly controls the active power and reactive power by using phase angle and voltage magnitude. Hence the PLL is not necessary in power synchronization control.

The power synchronization provides an inherent synchronization with grid in steady-state similar to a synchronous generator (SG). Basically, SGs do not have any limitations for connection to weak systems, consequently control methods, such as power synchronization which mimic SG's characteristics can effectively enable VSCs integration in very weak grids. The main characteristic of the proposed controller is it enables self-synchronization of a VSC in weak grids. This means that the controller does not need a separate synchronization unit and it automatically synchronizes itself with the grid. Self-synchronization is a new concept, and its importance is more pronounced in weak grids.

The main control strategies proposed for micro grids are, the centralized approach, the master slave technique and frequency/angle and voltage droop. Among them, since droop control utilizes only local information, it is the most adopted control technique for MGs to enhance system reliability and realize a complete autonomous control structure. The main objective of the droop control during islanding mode is to share total MG real and reactive powers demand among DG units according to their power capacities. In grid connected mode, DG units are required to generate preset real and reactive powers (P-Q bus) or generate preset real power at constant bus voltage (P-V bus).

In spite of their advantages, the conventional droop controllers have several drawbacks. Important among these are poor frequency regulation due to variable frequency operation, poor power sharing because of unmatched line impedances, low stability margin, lack of ability to work in all operational modes without reconfiguration, and transients associated with transitions between grid connected and islanding modes. It is well known that better power sharing accuracy can be achieved at the cost of lower stability margin. That is to say, there is a tradeoff between frequency regulation, system stability and accurate power sharing.

Stability of a droop-controlled MG can be improved using either supplementary control or adaptive droop gains. To mitigate problems associated with the conventional droop control, an alternative approach is to use load angle droop instead of frequency droop. The angle droop provides a constant frequency operation which is the main benefit; however, it suffers from poor power sharing and low stability margin. This is more pronounced when the load angle is large.

Motivated by the aforementioned challenges, a linear control of VSC in weak grids is proposed in this paper. This paper proposes a general control strategy, for both converter- and synchronous-machine-based DG units in MGs, based on a combined angle-frequency droop controller with improved dynamic performance.

As compared to previous autonomous control strategies, the proposed controller has the following advantages. 1) The proposed strategy combines frequency and angle droop strategies, therefore better power sharing accuracy can be obtained. In addition, designer has more degrees of freedom to select droop gains since there are two droop loops. Satisfactory static and dynamic performances can be simultaneously fulfilled by proper selection of these two constants. 2) It has a general structure for grid-connected and isolated modes of operation without a need for reconfiguration. This helps to mitigate problems due to islanding detection delay or non-detection zones and controller strategy changes subsequent to islanding. The most common approach for power management in islanded operation of VSCs is frequency droop.

2. Proposed Controller Topology

This paper focuses on the development of a linear power damping control strategy for VSC units in weak grids with applicability to both grid-connected and islanded modes of operation. Fig. 1 shows the schematic view of a grid-connected VSC supplying a local load.

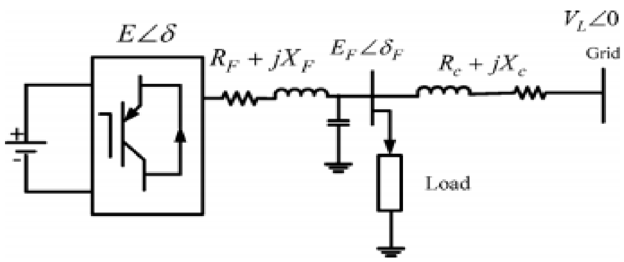

Figure 1: Circuit Diagram of a Grid-Connected VSC

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The DG is connected to its local load bus through connecting impedance (R + jX) including filter (R_F + jX_F). The real and reactive powers of each DG unit supplied to the bus are given by

$$P = \frac{E}{R^2 + X^2}(XV_L \sin\delta_{DG} + R(E - V_L \cos\delta_{DG})) \quad \text{.... (1)}$$

$$Q = \frac{E}{R^2 + X^2}(RV_L \sin\delta_{DG} + X(E - V_L \cos\delta_{DG})) \quad \text{...... (2)}$$

In highly inductive lines, the injected real power is mainly regulated by the load angle whereas reactive power is regulated by VSC voltage amplitude (E). According to the conventional droop control, the frequency (ω) and voltage amplitude (E) are obtained as

$$\omega = \omega_0 + mP \quad \text{......................... (3)}$$

$$E = E_0 + nQ \quad \text{......................... (4)}$$

The frequency and voltage droops form a communication-free medium to share real and reactive power among DG units proportional to their power capacities. The droop constants are given by

$$m = \frac{\Delta\omega_{max}}{P_{max}} \quad \text{...................... (5)}$$

$$n = \frac{\Delta E_{max}}{Q_{max}} \quad \text{............................ (6)}$$

The voltage generation principle is similar to an SG where the voltage frequency and load angle are tuned by power damping-synchronizing loop, whereas the voltage amplitude is given by voltage regulation loop similar to an automatic voltage regulator (AVR). Unlike SGs, the output power angle of a VSC can be changed instantaneously without changing frequency; therefore using the angle droop is another way to share real power. As a matter of fact, since real power is controllable through load angle, there is no need to vary frequency to regulate power; thus, frequency is just employed as a medium for angle tuning. The governing equation in this case is as follows:

$$\delta = \delta_{set} + dP \quad \text{..................... (7)}$$

The angle droop provides a constant frequency operation.

A. Concept of Synchornaisation and Power Dmaping

In a grid-connected VSC, the linear controller provides active damping and synchronization power to reduce power and frequency oscillation. During the study state operation the controller synchronize the VSC with grid. Fig. 2 represents the block diagram of the proposed controller. The controller consists of three loops such as the angle, frequency and power loops and consequently benefit from their advantages simultaneously. Constant frequency operation and accurate power sharing can be realized by combined angle-frequency droop.

The controller is implemented in polar coordinates and directly regulates the error output voltage vector amplitude and angle. According to the frequency, the reference of the load angle is determined and as function of load angle error the real power reference is obtained. Then VSC's instantaneous frequency and load angle are adjusted by power synchronization loop.

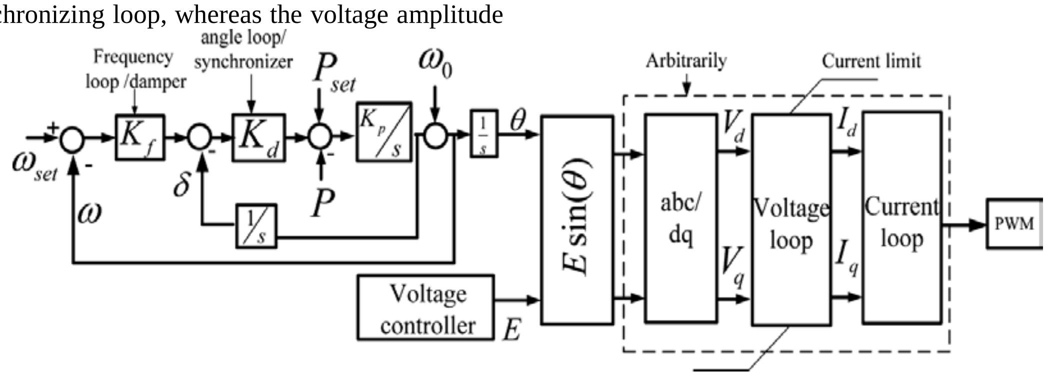

Figure 2: Circuit diagram

The angle and frequency loops play two various roles; first, they behave like dampers to mitigate angle and frequency oscillations. Second, they provide synchronizing power. The damping and synchronizing power components are given by

$$\text{Damping Power} = \Delta P_{damp} = -K_f \Delta\omega \quad \text{.............. (8)}$$

$$\text{Synchronizing power} = \Delta P_{synch} = -K_f K_d \Delta\delta \quad \text{....... (9)}$$

The synchronizing power attempts to return load angle to its equilibrium point subsequent to transients while damping power is responsible for preserving frequency stability and mitigating frequency oscillations. Hence, the proposed topology offers more damped transient behavior as compared to the conventional frequency or angle-droop controllers because of these extra loops. In autonomous mode, and act as angle and frequency droops while the angle droop is the main power sharing loop.

The VSC track frequency and angle deviations of the grid and automatically synchronizes itself with the grid. The reference frequency (ω_{set}) in the frequency loop is set equal to the grid frequency, and in steady-state conditions, the VSC produces the reference power (P_{set}).

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The power-damping control law for a VSC is proposed as

$$\frac{d\Delta\omega}{dt} = -K_p K_f K_d(\omega - \omega_{set}) - K_p K_f \delta - K_p (P - P_{set}) \quad (10)$$

The relationship between the VSC frequency and the load angle is

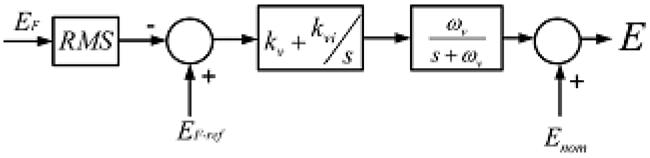
$$\frac{d\delta}{dt} = \Delta\omega \quad \ldots\ldots\ldots (11)$$

To eliminate the switching effect superimposed on the real power, a low-pass filter can be adopted and the filtered power (average power) is fed to the controller. This low-pass filter also gives more degrees of freedom in the control design and may introduce more damping for angle and frequency oscillations.

B. Voltage Controller

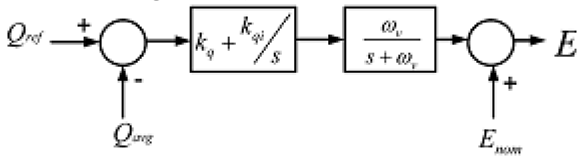
The reactive power of a DG unit can be controlled to 1) regulate the terminal voltage (PV bus) or 2) achieve a specific output reactive power (PQ bus). The Fig. 3(a) & (b) shows these two different variants. In the first, the voltage reference is compared to the actual output voltage. In order to track the reference voltage, a proportional-integral (PI) controller is employed aiming at compensating the input error by proper adjustment of VSC's output voltage.

The output of the PI controller is processed by a low-pass filter and finally the VSC's voltage amplitude reference is obtained. The low-pass filter plays two different roles. First, it offers more degrees of freedom to tune the low-pass filter cut-off frequency and PI controller parameters such that satisfactory transient and steady-state performances are achieved. In weak grids, usually it is essential to regulate the grid-voltage at the point of common coupling, thus PV bus is the common approach in weak grids.



(a)

Figure 3(a): P-V Bus Control



(b)

Figure 3(b): P-Q Bus Control

An alternative to the voltage control is reactive power regulation as shown in Figure 3. (a). However, this is not the common case in weak grids. This is due to the fact that the P-Q control strategy significantly degrades DG stability in weak grids as compared to the P-V control. Similar to Figure 3. (b), a low-pass filter exists after the PI controller to mimic the flux decay behavior of an SG. This low-pass filter allows the suppression of voltage oscillations while voltage tracking time-response and steady-state error are still kept within acceptable limits. With the help of MATLAB SIMULINK the PWM signal is generated.

A closed loop is made for continuous measure of voltage and current in grid. If any change occurs the controller will make necessary modifications and give a PWM signal to VSC. The VSC will supply real or reactive power to weak grid according to its need.

3. Enhance Performance Under Different Power Levels

The simulation is carried out using the test system (Fig.4) and the parameter of controllers inputs are referred from standard IEEE papers. The simulation study is conducted in MATLAB/SIMULINK model.

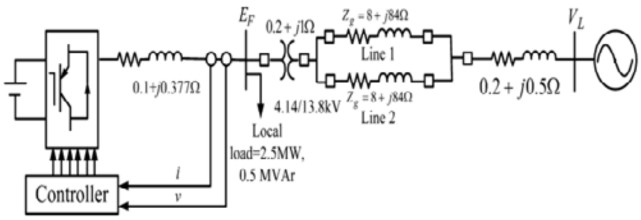


Figure 4: Simulated Test System

The system is composed of a 7.0 MW VSC, filter, local load, transformer and an interface line connecting the VSC to a grid. The impedance 0.2+ j0.5Ω is the equivalent impedance of the stiff source referred to the distribution level. The simulation study was conducted The DG unit supplies the local load at its output terminal and is connected to a stiff grid through a very weak interface with total impedance of 43.7Ω . Since the connecting line is almost inductive, the power capacity of the interface line is approximated by

$$P \cong \frac{E_F V_L}{X} Sin\delta_F \quad \ldots\ldots\ldots (11)$$

Where the notations are defined in Fig. 1and X is the total reactance of the transformer, line and stiff grid(X=42+1+0.5=43.5Ω). Therefore, the maximum real power transfer capacity of the connecting line is equal

$$P_{max} = 13880^2/43.5$$
$$\approx 4.44\text{MW}.$$

Since the local load power at the rated voltage is 2.5 MW, thus the VSC's maximum power capacity is about 7 MW. The DG works as a PV bus aiming at keeping the filter output voltage (E_F) constant during grid connection. System performance at low- and high-power references, transition to islanding, self -synchronization is studied.

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Table 1: Controller Parameters

Parameter	*Value (SI units)*
VSC maximum power capacity	7MW
VSC voltage (L-L $_{rms}$)	4160V
$E_{f\text{-}ref}$(Phase maximum voltage)	3400V
K_f	5
K_d	$1{*}e^5$
K_p	0.1
K_v	200
K_{vi}	100

4. Simulation Scenario

A. Power Injection and Grid Restoration

The simulation response of real power, voltage and current are shown in Fig.5 and the frequency response is shown in Fig.6.

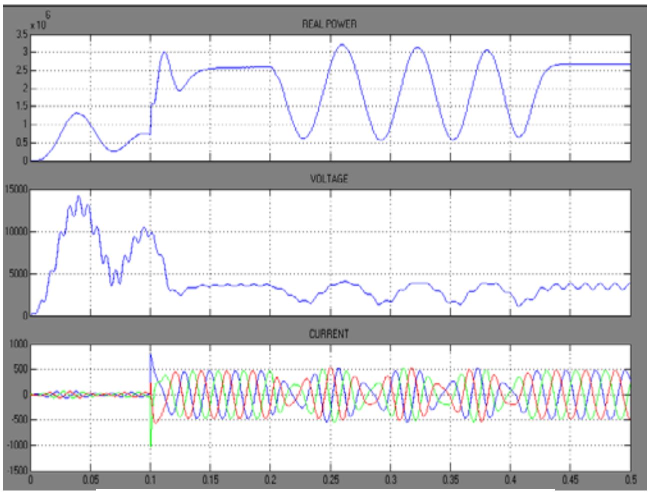

Figure 5: Output waveform of Real Power

Low Power Injection

To study the behavior of the controller in a wide range of operating points, it is assumed that we are having only single load till 0.1s.the power reference is increased from 0.5MW to 1.5MW it has a slight oscillation and remain stable in 0.8MW.Here the current is less with severe oscillations and voltage magnitude is increased with high oscillations.

High Power Injection

At t=0.1s, the load circuit breaker is closed and one more load is added .the reference power is varied between1.5MW to 3.0MW.The response is smooth but with larger rise time; however, it is still stable with damped response and the output power reaches 2.5MW. The current is also increased and the voltage oscillations are reduced.

Transition to Islanded Mode

Islanded operation is another scenario that may occur in DG applications to supply local critical loads. At, t=0.2s the VSC is switched to the islanded mode due to a fault in the grid. No controller-mode switching action or reconfiguration is required. While referring the waveforms there are oscillations in the power, voltage and current.

Grid Restoration

It is common that a recloser automatically reconnects a DG unit to the main grid after a special time period (usually 1 s). This is due to the fact that most of faults are cleared after few cycles. In this case, connection occurs without synchronization which may lead to severe transients as a result of frequency and angle mismatch of both sides of the recloser at the moment of connection. Weak grids suffer more from the resynchronization transients. The real power response is 2.5MW.The response is smooth and well damped. Even the current oscillation is also damped.

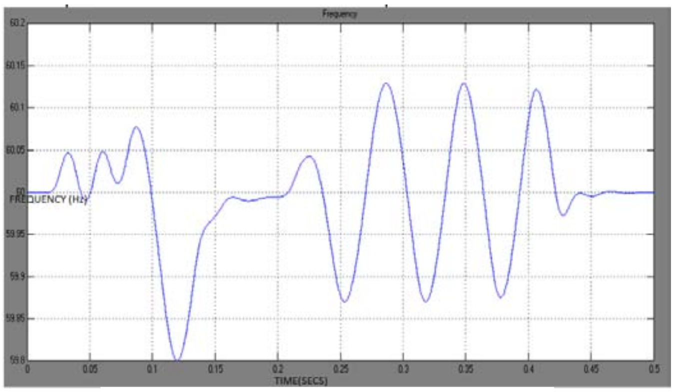

Figure 6: Output Waveform of Frequency

Case 1: The frequency is having a higher value till 0.1s and also oscillations for low power injection.
Case 2: In this case 0.1s to 0.2s it shows a lesser value almost close to zero for high power injection.
Case 3: While noticing the frequency wave in the islanding mode it got lot of disturbances from 0.2s to 0.4s.
Case 4: But after grid restoration there is a stable frequency of 60 Hz from 0.45s.

5. Conclusion

This paper gives a new control method to improve the performance of the weak grids. The linear power damping controller mimics SGs with extra power damping-synchronization capability providing self-synchronization with the grid which eliminates the need for a PLL. A wide variety of scenarios have been applied to verify the effectiveness of the proposed linear controller. System performance at low and high-power references, transition to islanding, self-synchronization is studied.

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